

30-6-2001

A novel concept for a $\bar{\nu}_e$ neutrino factory

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Abstract

The evolution of neutrino physics demands new schemes to produce intense, collimated and pure neutrino beams. The current neutrino factory concept implies the production, collection, and storage of muons to produce beams of muon and electron neutrinos at equal intensities at the same time. Research and development addressing its feasibility are ongoing. In the current paper, a new neutrino factory concept is proposed, that could possibly achieve beams of similar intensity, perfectly known energy spectrum and a single neutrino flavour, electron anti-neutrino. The scheme relies on existing technology.

Submitted to Phys. Lett. B

arXiv:hep-ex/0107006v4 15 Jul 2001

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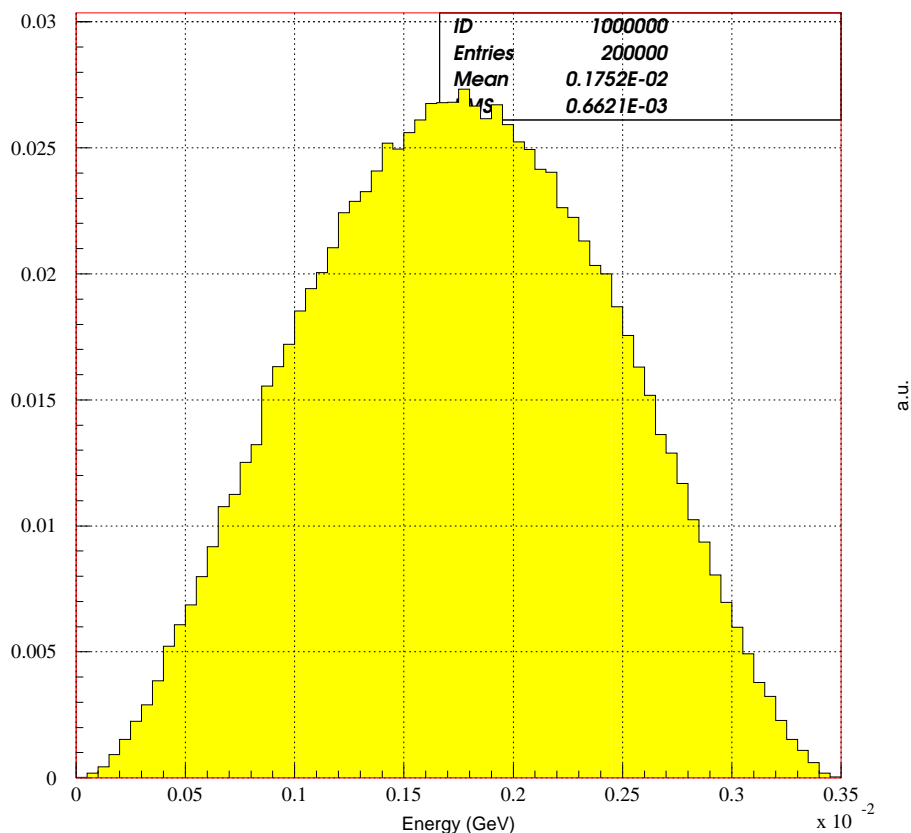


Figure 1: Neutrino energy spectrum in the centre-of-mass frame for a ${}^6\text{He}$ decay.

1 Introduction

The demand for better neutrino beams is correlated to the considerable improvement in neutrino detectors, and to the recent exciting claims of evidence for neutrino oscillations by various experiments. In particular, solar, atmospheric and accelerator neutrinos appear today to oscillate (and therefore should have non-zero masses) in a way that it is hard to accommodate in a unique picture, given current theoretical understanding. Speculation and *ad-hoc* theories abound in the absence of decisive experiments. Obviously, a high intensity neutrino source of a single flavour, no background and perfectly known energy spectrum and intensity could be decisive both for oscillation searches and precision measurement of the lepton mixing parameters.

2 The concept

It is proposed to produce a collimated $\bar{\nu}_e$ beam by accelerating, at high energy, radioactive ions that will decay through a beta process.

The radioactive ion production and acceleration to low energy (several MeV) have already been performed for nuclear studies, and various techniques have been developed [2], e. g. at CERN ISOLDE.

The acceleration of the positively charged atoms to about 150 GeV/nucleon is already done in the CERN PS/SPS accelerators for the heavy-ion programme.

The storage of the radioactive ion bunches in a storage ring could be very similar to what is being studied for the ‘conventional’ neutrino factory scheme [7].

Two important features have to be outlined.

- Unprecedented beams of single flavour neutrinos with energy spectrum and intensity known a priori. Moreover, this flavour ($\bar{\nu}_e$) is different from that which is dominant for conventional beams (ν_μ). This feature allows new precision measurements (oscillation searches at small mixing angles, nuclear physics studies) to be performed.
- The second peculiar characteristic is given by the fact that the neutrino parent, the ion, has a rest

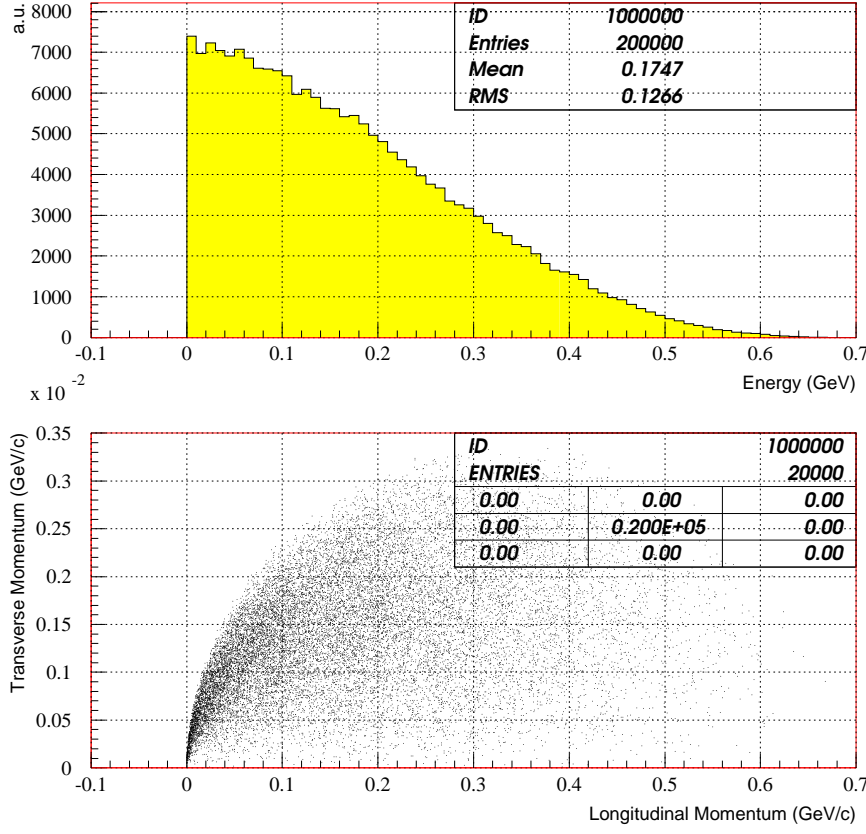
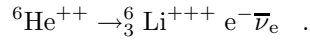


Figure 2: ‘Boost’ focusing of the neutrinos.

energy much larger than the neutrino energy in the centre-of-mass frame. This allows a focused beam of low-energy neutrinos to be produced, which has been impossible up to now. This feature is particularly important for long-baseline neutrino studies.

2.1 Nuclear beta decays

As a guideline, a textbook atomic β^- decay which has well-known characteristics and good features for neutrino production is considered:



Its half-life $T/2$ is 0.8 s, and the beta decay endpoint E_0 (maximum energy of the emitted electron) is 3.5 MeV. The energetic endpoint of the electron and the atom lifetime are, unfortunately, correlated by the ‘Sargent rule’ [4]. In substance, the width of the unstable initial state is proportional to the fifth power of the energy endpoint, so that a low E_0 value implies an almost stable atom. For neutrino production and long-baseline studies, contemporaneous low value of E_0 and $T/2$ would be the best solution, in contradiction with nature. A deeper study of potential neutrino sources is mandatory but, for the sake of illustration, ${}^6\text{He}$ is a valid starting point. The energy spectrum of the electron produced in the ${}^6\text{He}$ beta decay has been extensively measured and is well described theoretically (for energies larger than the electron mass and valid without corrections only for light nuclei) by the simple analytic formula

$$N(E)dE \approx E^2(E - E_0)^2 ,$$

where E is the electron energy. The neutrino spectrum is completely known by the laboratory measurement of the associated electron (without involving a neutrino measurement) since $E_e + E_\nu \approx E_0$ because of the large mass of the nucleus. Fig. 1 shows the neutrino spectrum from ${}^6\text{He}$ decays when the source is in the same reference frame as the experimenter.

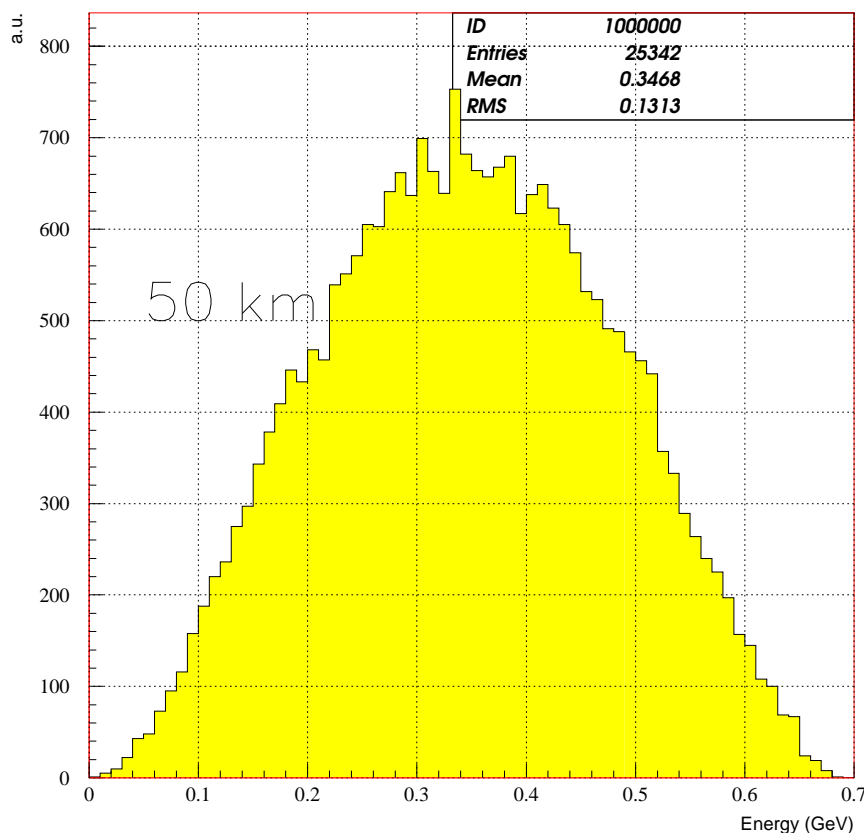


Figure 3: Neutrino spectrum 50 km from the source.

2.2 The relativistic effect

Suppose that the ${}^6\text{He}$ atom is accelerated up to a value of $\gamma = 100$, achieving a typical energy per nucleon currently obtained in the heavy-ion runs of the CERN SPS. In the laboratory frame, the neutrino transverse momentum (with respect to the beam axis) is identical to that observed when the atom is at rest: 1.75 MeV on average. In contrast, the average longitudinal momentum is multiplied by a factor corresponding to γ_{He} and therefore neutrinos have typical decay angles of $1/\gamma_{\text{PARENT}}$, in our case 10 mrad. Special relativity also tells us that the neutrino energy in the forward direction is multiplied by twice the same factor, so that the average neutrino energy on a ‘far’ detector is expected to be 350 MeV.

A better insight into the correlations among the various distributions can be obtained by a simple Monte Carlo simulation. The laboratory spectrum of all produced neutrinos is shown in Fig. 2, together with the characteristic phase distribution in the $P_T - P_L$ plot that corresponds to the relativistic transformation of an isotropic distribution in the rest frame.

The effective characteristics of this type of beam can be observed by looking in more detail at the neutrino spectrum on an ideal detector in a far position. If the lateral dimensions of the detector are smaller than $1/\gamma_{\text{PARENT}}$ multiplied by the distance, the neutrino spectrum has no radial dependence and corresponds to the neutrino spectrum at rest, with an energy endpoint $E_0^{\text{LAB}} = 2 \times \gamma \times E_0^{\text{CMS}}$. This has been verified by the simple Monte Carlo simulation and is shown, for one case, in Fig. 3. The relative flux for various distances is reported in Table 1.

As in the case of the spectrum, even the neutrino flux intensity can be evaluated from first principles: the isotropy of the decay in the centre-of-mass frame, the knowledge of the E_0 endpoint value and the acceleration energy (γ).

It is important to compare the focusing properties with those of a conventional neutrino factory beam. The comparison should be done for identical values of $\langle E \rangle / L$: a value of 7×10^{-3} GeV/km is arbitrarily chosen, which corresponds to a 50 km baseline for the beta-beam and 4857 km for the conventional neutrino factory beam produced by 50 GeV muons [7]. The flux of neutrinos reaching the

Table 1: Relative flux from a $\gamma = 100$ ($\langle E_\nu \rangle = 350$ MeV) ${}^6\text{He}$ beta-beam at various distances onto a detector of 1 m^2 . Corresponding $\langle E \rangle / L$ values are also reported.

Distance (km)	Relative flux ($\nu/\text{m}^2/\text{ions}$)	$\langle E \rangle / L$ (GeV/km)
1	3.0×10^{-3}	0.35
3.125	3.5×10^{-4}	0.11
6.25	4.4×10^{-5}	5.6×10^{-2}
12.5	1.7×10^{-5}	2.8×10^{-2}
25	5.2×10^{-6}	1.4×10^{-2}
50	1.4×10^{-6}	7.0×10^{-3}
100	3.8×10^{-7}	3.5×10^{-3}
200	8×10^{-8}	1.7×10^{-3}
400	2×10^{-8}	8.7×10^{-4}

far detector is $1.4 \times 10^{-6}/\text{m}^2$ in the case of the beta-beam and $8.0 \times 10^{-9}/\text{m}^2$ in the case of the conventional neutrino factory beam. After this, it has to be said that the collection efficiency comparison is essentially independent of the γ factor in both cases, if the comparison is made under identical $\langle E \rangle / L$ conditions.

3 Feasibility

Here, the challenges to the feasibility of beta-beams are reviewed aspect by aspect, and possible objections are anticipated.

3.1 Radioactive ion production

Various techniques have been developed in the nuclear physics community in order to produce unstable, radioactive nuclei. For a detailed review, the interested reader is referred to ref. [2]. Probably, the technique developed at CERN ISOLDE, called ISOL ion production, is the most suitable for a high intensity ${}^6\text{He}$ production. Today ISOLDE can produce up to $\approx 10^8$ ${}^6\text{He}$ ions per second [3], without a specific optimization for this atomic state. A significant improvement can be achieved in various ways: increased target thickness, optimized target converter, use of an ECR ionization source, higher proton energy [1]. It should be mentioned that a possible upgrade of the CERN accelerators by a Superconducting Proton Linac (SPL) would additionally improve the production rate, and such a facility has already been advocated and studied by the ISOLDE team [5] for nuclear physics experiments. The consequent further increase of proton energy and intensity could allow the production rate to be improved by two or three orders of magnitude, achieving the value of $10^{12}/\text{s}$ ${}^6\text{He}$ ions which is an important ingredient for an effective beta-beam.

3.2 Post-acceleration

Post-acceleration of ${}^6\text{He}$ ions does not differ in the substance from non-radioactive ion acceleration. Unlike the conventional neutrino factories, the acceleration time to reach the relativistic regime (where the dilatation of the decay time in the laboratory frame occurs) is not critical, being the ratio of the lifetimes 4×10^5 , and for example the acceleration cycles of the CERN PS multi-purpose synchrotron are affordable. REX-ISOLDE is indeed a facility under commissioning for post-acceleration of a wide spectrum of radioactive ions. Once the relativistic regime is achieved (PS), the injection into a larger machine, CERN SPS for example, could take the beam to the required energy before it is sent to the storage ring.

Given that the beam is radioactive, one could object that the radioactive pollution in the accelerator would seriously compromise the beta-beam's feasibility. In fact, the radioactivity rate could be tolerable because its characteristics are significantly different from those of pure losses, and moreover it decreases at high energy because of the relativistic time dilatation due to the energy boost. Without giving a proof, obtainable only by a detailed study on the specific accelerator, a possible argument in favour of it is presented below.

A beta-beam induced radioactivity is a perfectly known process, where an accelerated ion nucleus decays into a harmless neutrino, a negative electron, and an ion whose charge differs by one unit from that of its parent. The decay rate decreases linearly with the increasing energy because of the boost, therefore the average decay occurring during acceleration has a low-energy parent and is in the low-energy section of the accelerator. The average energy of the escaping electron is about 300 times lower than that of its parent, while the lithium ion has of course the same energy as the decaying helium. The electrons can be easily stopped by thin metallic shields, and produce no secondary neutrons. The lithium ions have a

different charge. Their trajectories will therefore change and follow different and well-known orbits; the collisions of the decayed nuclei will thus occur in well-localized places. Therefore it is probably possible to shield the machine where the trajectories of the daughter ions are expected.

3.3 The storage ring

The storage ring must:

- have a straight section whose length, relative to the total length, is as long as possible;
- store the maximum number of bunches, to allow the ions time to decay;
- be immune from the radioactive ion decays.

The first two of these requirements are similar to those of a conventional neutrino factory storage ring, and detailed studies have already been performed. It is assumed to be reasonable to store 140 bunches with a relative length of the straight section towards the detector of 28.7% [7]. The immunity to radioactive decays can be obtained in the same way as discussed for the accelerating machines. As an interesting possibility, it is noted that at the end of the straight sections the intensity of lithium ions and electrons is maximum: A dedicated dipole-like optics could separate the electrons from the helium and from the lithium. Electrons could provide a very direct intensity monitor. The high-energy lithium ions could be recycled to activate the ion source and therefore improve the efficiency of the radioactive ion production.

3.4 Baseline, energy and intensity considerations

Order-of-magnitude performances of the acceleration scheme can be based on current efficiencies of existing machines. A loss rate of 50% in the accelerator and a 140 s storage time in the storage ring are assumed, but the neutrino interaction rate is **not** included.

Table 2: Summary of possible performances and characteristics of a beta-beam.

⁶ He ions production	10 ¹² /s	
⁶ He accelerator efficiency	50%	
⁶ He final energy	100 GeV/nucleon	
Storage ring bunches	140	
Straight section relative length	28.7 %	
Storage time	140 s	
Running time/year	10 ⁷ s	
Neutrino flux at 1 km	3 × 10 ¹⁵ /m ² /year	⟨E⟩/L = 0.3 GeV/km (LSND)
Neutrino flux at 12.5 km	1.7 × 10 ¹³ /m ² /year	⟨E⟩/L = 2.8 × 10 ⁻² GeV/km (CNGS)
Neutrino flux at 25 km	5.2 × 10 ¹² /m ² /year	⟨E⟩/L = 1.4 × 10 ⁻² GeV/km (NuFact)
Neutrino flux at 50 km	1.4 × 10 ¹² /m ² /year	⟨E⟩/L = 7.0 × 10 ⁻³ GeV/km (Super-beam)
Neutrino flux at 100 km	3.8 × 10 ¹¹ /m ² /year	⟨E⟩/L = 3.5 × 10 ⁻³ GeV/km (SuperK Atm)

A flux comparison with existing beams, proposed super-beams, and expected neutrino factory performances allows an estimation of whether the neutrino flux achieved by a beta-beam could have a significant impact on neutrino physics understanding. The reader is reminded that the CERN Neutrinos to Gran Sasso (CNGS) beam aims at an integrated flux of $3.5 \times 10^{11} \nu_\mu/\text{m}^2/\text{year}$ with a 17.7 GeV average energy [8][9]. One of the discussed super-beam options [10] has the goal of $2.4 \times 10^{12} \nu_\mu/\text{m}^2/\text{year}$ at 260 MeV. The conventional neutrino factory from muon decay aims to $2.4 \times 10^{12} \nu/\text{m}^2/\text{year}$ at 34 GeV. Table 2 shows the possible neutrino fluxes of a beta-beam at comparable ⟨E⟩/L values of physics relevance.

The reader is explicitly warned against making comparisons that do not take into account the physics objectives. At first glance, for example, the super-beam and the beta-beam have similar energy and similar intensity. But the different neutrino flavour of the beta-beam has a significant impact on the main super-beam physics objective [11]: the mixing angle θ_{13} can in fact be measured in the beta-beam by a direct disappearance experiment or by neutral-current to charged-current analysis. Then, with a much lower background, a better knowledge of the neutrino flux and a better knowledge of the neutrino spectrum, the beta-beam can also perform in a better way the model-dependent measurement based on the appearance of $\bar{\nu}_\mu$ from $\bar{\nu}_e$ through indirect mixing with the third family, the beam related uncertainties being dominant [11] in the case of the super-beam.

4 Impact on possible measurements

To evaluate the physics impact of a beta-beam, the physics goal has to be specified in view of the low maximum energy, the focusing property and the different neutrino flavour with respect to other

accelerators.

4.1 Oscillation physics: appearance and disappearance

Disappearance measurements are particularly attractive since both intensity and spectrum of the source are perfectly known on the basis of a non-neutrino measurement. These disappearance experiments have the advantage of being sensitive to oscillation also if the value of Δm^2 is much larger than the typical $\langle E \rangle / L$ (hereafter called normalized energy) of the experiment. For the case in which Δm^2 is comparable to the normalized energy, the experiment is ideally suited to a precision measurement of the $\bar{\nu}_e$ disappearance, with a sensitivity only limited by statistics. When Δm^2 is smaller than the normalized energy, i.e. the experiment is too near to the source, the sensitivity of a disappearance experiment is typically seriously compromised and does not appear to be competitive with appearance detection for the same normalized energy.

A different and important evaluation of the oscillation parameters can be performed by studying the ratio of neutral-current to charged-current interactions. In fact the study of $\nu_e \rightarrow \nu_\tau$ oscillations is particularly difficult nowadays, since there are only a few available ν_e or ν_τ sources¹⁾ (solar and reactor neutrinos), which have furthermore a very low energy and peculiar characteristics (non-pulsed time structure, for example).

In conclusion, a disappearance beta-beam experiment could be a very large, simple electromagnetic calorimeter capable of measuring the energy of one electron and located at a distance that makes the normalized energy comparable to the Δm^2 value to be measured. This detector, by timing, could be synchronized to the pulsed structure of the storage ring in order to minimize backgrounds. It is impossible not to think of the large water Cherenkov detectors, such as SuperKamiokande or ANTARES.

Appearance experiments with beta-beams probably have to be limited to muon neutrino appearance. Even if it was possible to increase the ion energy to achieve the cross-section threshold necessary for tau production (ν_τ appearance), this would require substantial evolution of the accelerating technology: Machines with the characteristics of LHC, for example, employ sophisticated superconducting magnets which – probably – are not suited to the larger ionization loss in the optical elements of the ring. The boost effect, in addition, would imply a large storage capacity of the accumulator due to the additional lifetime dilatation.

Anyway, ν_μ appearance experiments with beta-beams have two interesting possibilities connected to the absence of other flavours in the beam.

The first is related to the long-baseline measurements, since the far detector can be much simpler than a conventional neutrino factory detector, and it should only differentiate a muon track from an electron shower. This simplicity could be reflected in a larger overall mass than that of a magnetic detector typically required in a conventional neutrino factory scheme to separate the huge background induced by neutrinos of the same flavour but opposite lepton number. Therefore, the ideal beta-beam appearance detector is a very large, simple detector with good muon identification properties. Again, it is impossible not to think of the large water Cherenkov detectors, as already studied in ref. [11] in the same energy regime.

The second possibility is connected to short-baseline measurements: If the MiniBoone experiment validates the LSND oscillation claim, a beta-beam experiment looking to $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$ oscillation without backgrounds could allow unprecedented measurements of oscillations in the region of Δm^2 relevant to astrophysics and cosmology. At the moment, no pure sources of ν_μ or ν_e are available to appearance experiments which have to explore the domain of $\sin^2 \theta_{12} \approx 10^{-4}$.

4.2 Precision physics

The high intensity and the absence of backgrounds make a beta-beam very interesting in the domain of nuclear studies with neutrinos. The small maximum energy, however, limits the scope of the investigations to this domain, which could be very relevant anyway in order to measure the cross-section on different target materials of $\bar{\nu}_e$ neutrinos from astronomical sources.

4.3 Are CP violation measurements still possible?

An evident advantage of the conventional neutrino factory beams is the possibility to accelerate muons or anti-muons to produce neutrinos of opposite lepton number. This opens the possibility to measure CP violation effects in the leptonic sector. Despite the difficulty in identifying the experiment parameters which will allow an effect to be observed, this measurement is clearly of maximum importance.

¹⁾ The small ν_e and ν_τ contributions in conventional beams are not considered, since they are present only for high-energy neutrinos and therefore do not allow a significant exploration of the region of Δm^2 below a few eV^2 , which is nowadays the focus of the attention.

A beta-beam has the crucial advantage of a lower energy and better focusing, which is reflected in a larger explorable domain of normalized energy values (see Table 1). But anti-helium atoms are impossible to produce. The solution is to accelerate a different atom, which has a superallowed β^+ transition [6]; for example,

$${}^{18}_{10}\text{Ne} \rightarrow {}^{18}_9\text{F}^- e^+ \nu_e \quad ,$$

which has a half-life $T/2$ of 1.6 s and an endpoint $E_0 = 3.2$ MeV. Other candidates exist; for example, ${}^{34}_{17}\text{Cl}$ and ${}^{38}_{19}\text{K}$ have short lives and produce ν_e in their beta decay.

5 Conclusions

An alternative neutrino factory scheme can produce $\bar{\nu}_e$ beams from the beta decay of boosted ions. The efficient focusing makes it very suitable for explorations at low Δm^2 values. The unprecedented beam flavour, the known spectrum, and the perfect purity make it attractive for both appearance and disappearance oscillation experiments, and for new precision neutrino physics. The technology to produce, accelerate and store radioactive ions has already been explored.

Neutrino physics recent discoveries probably represent the most important opportunity to probe the Standard Model understanding. Any improvement of the current artificial neutrino acceleration technology should therefore be investigated. Up to now, many have considered focused low-energy neutrino beams impossible.

6 Acknowledgements

The author is indebted to T. Nilsson, J. Panman and B. Saitta for their attention, comments and suggestions.

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